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Title: Magnetoplasmonic Manipulation of THz Transmission and Faraday Rotation Using Graphene Micro-Ribbon Arrays

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Magnetoplasmonic Manipulation of THz Transmission and Faraday Rotation Using Graphene Micro-Ribbon Arrays

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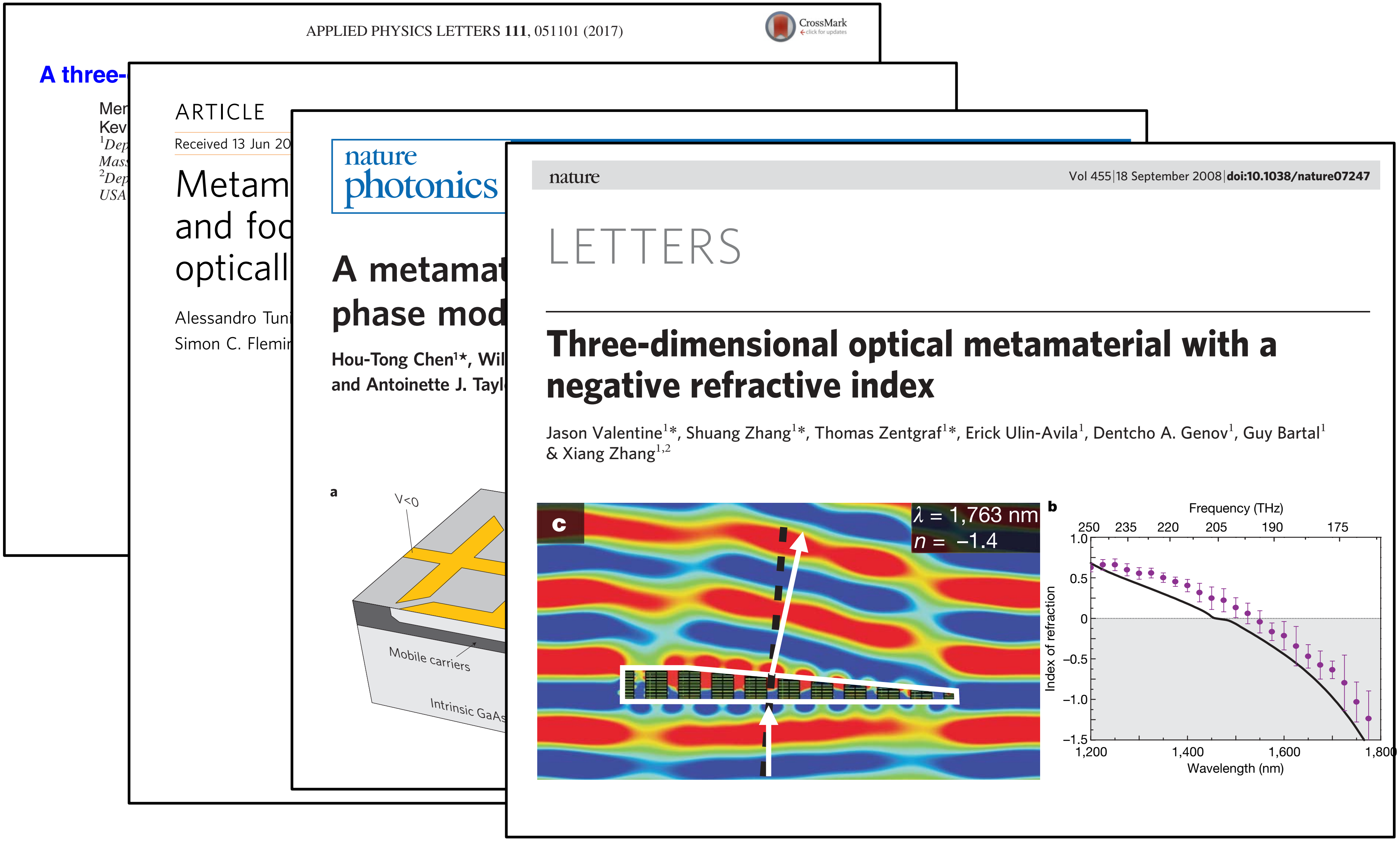
San Jose, CA

Metamaterials have been successful in terahertz manipulation



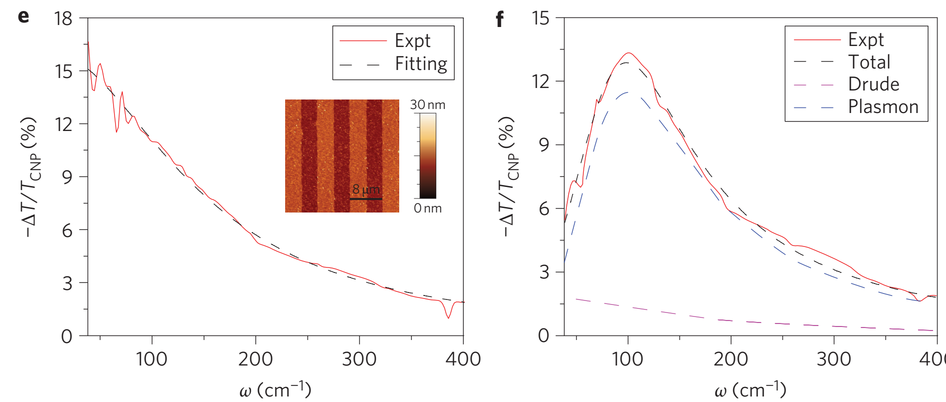
Metamaterials to metasurfaces

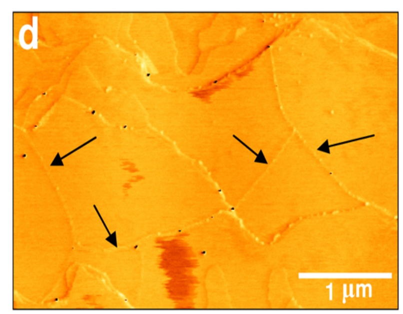
- Volumetric losses and complex fabrication make metamaterial applications challenging
- Metasurfaces have greater compatibility with conventional processing and lower loss due to their dimensionality
- Integrating reconfigurable materials into metasurfaces adds another degree of flexibility
- May allow for active tuning of the metasurface’s response

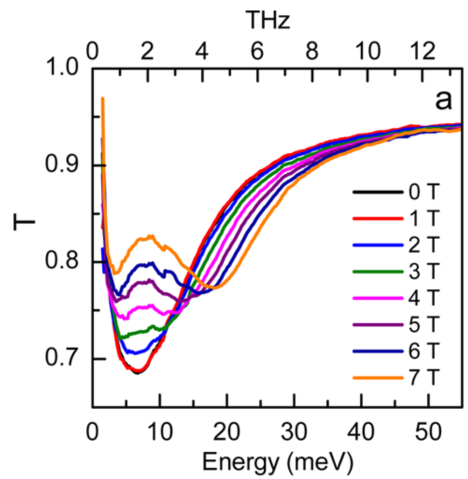
Graphene-based THz metasurfaces

Why graphene?

- Easy growth and patterning on THz-transparent substrates
- Graphene plasmon resonance can be tuned through in-plane periodicity
- The optical response of graphene is strongly influenced by magnetic fields

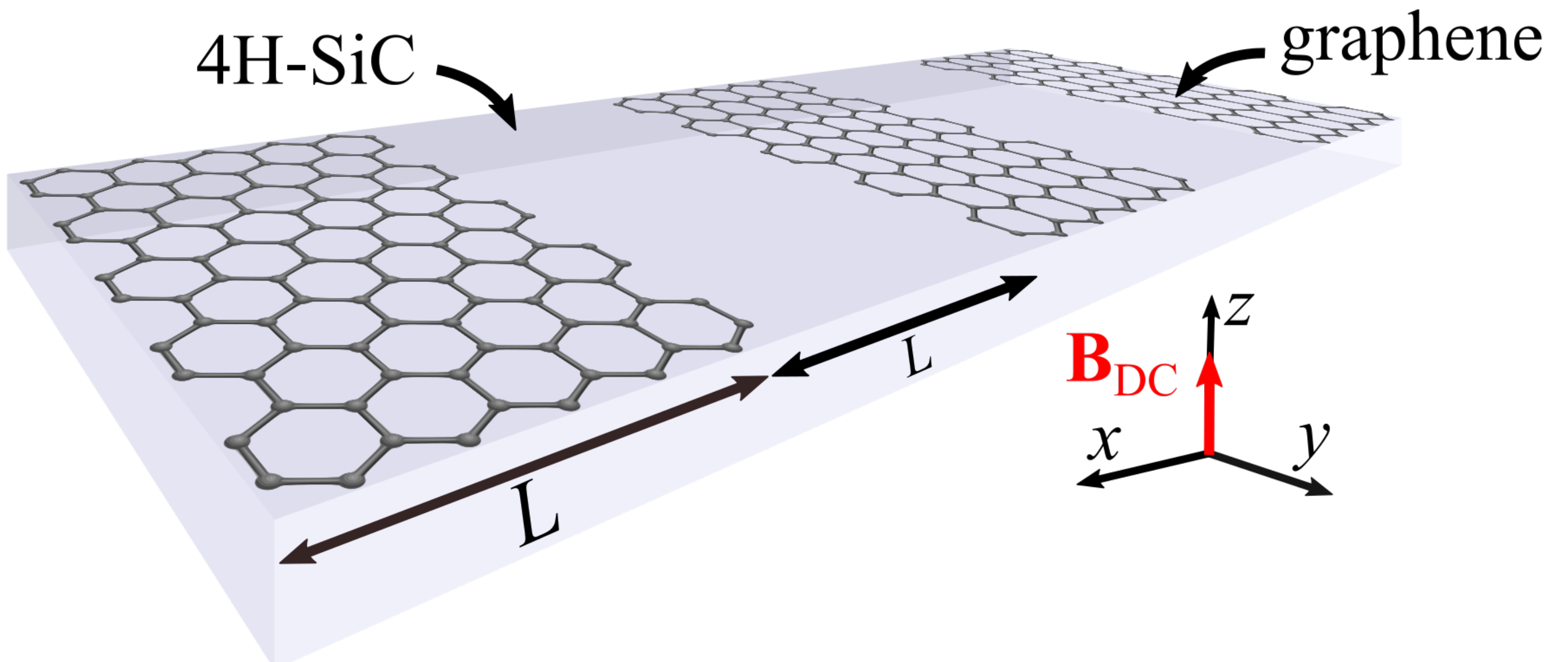






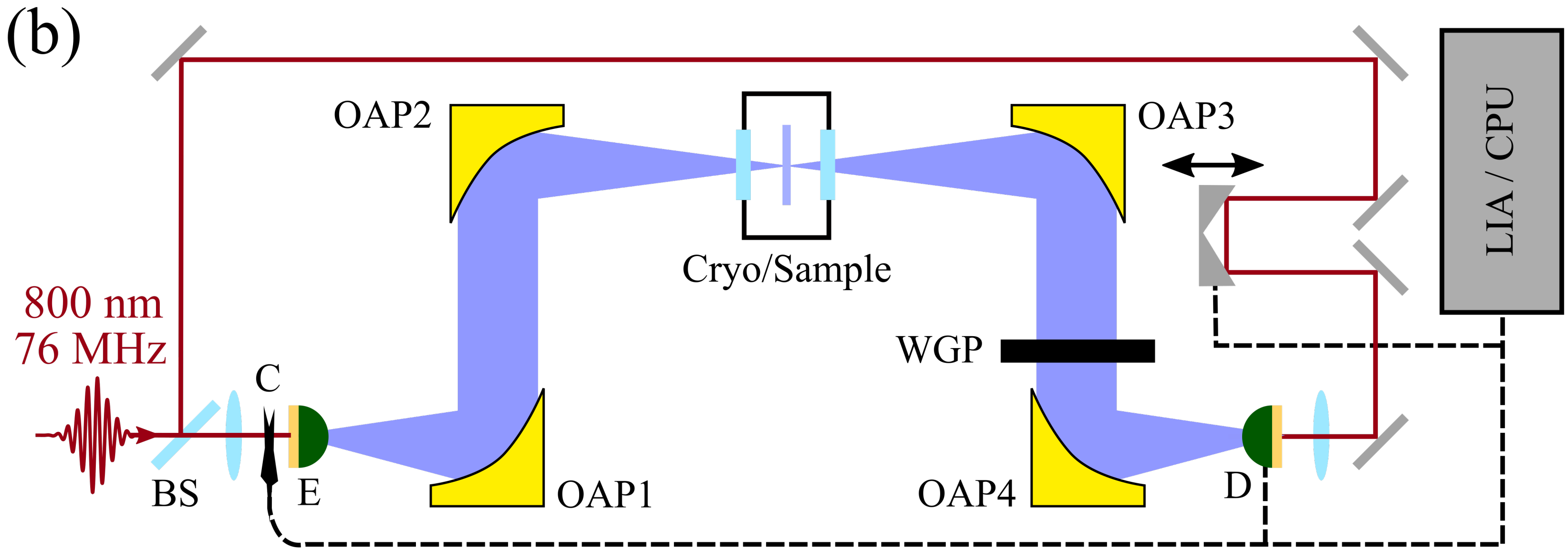
L. Ju, et al., Nature Nanotech. (2011)
I. Crassee, et al., Nano Lett. 12, 2470 (2012)

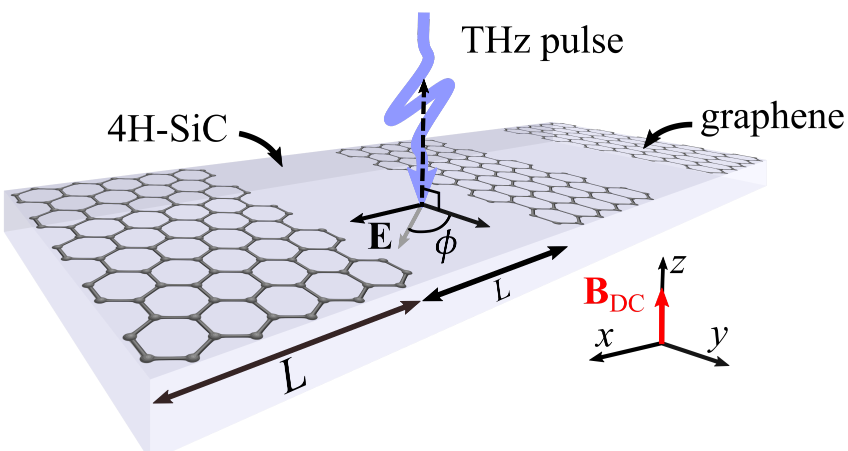
Graphene-based THz metasurface



- Graphene is epitaxially grown on 4H-SiC substrate
- Patterned into ribbons using e-beam lithography
- Several samples with different L, all with 50% filling ratio

THz magneto-optical spectroscopy

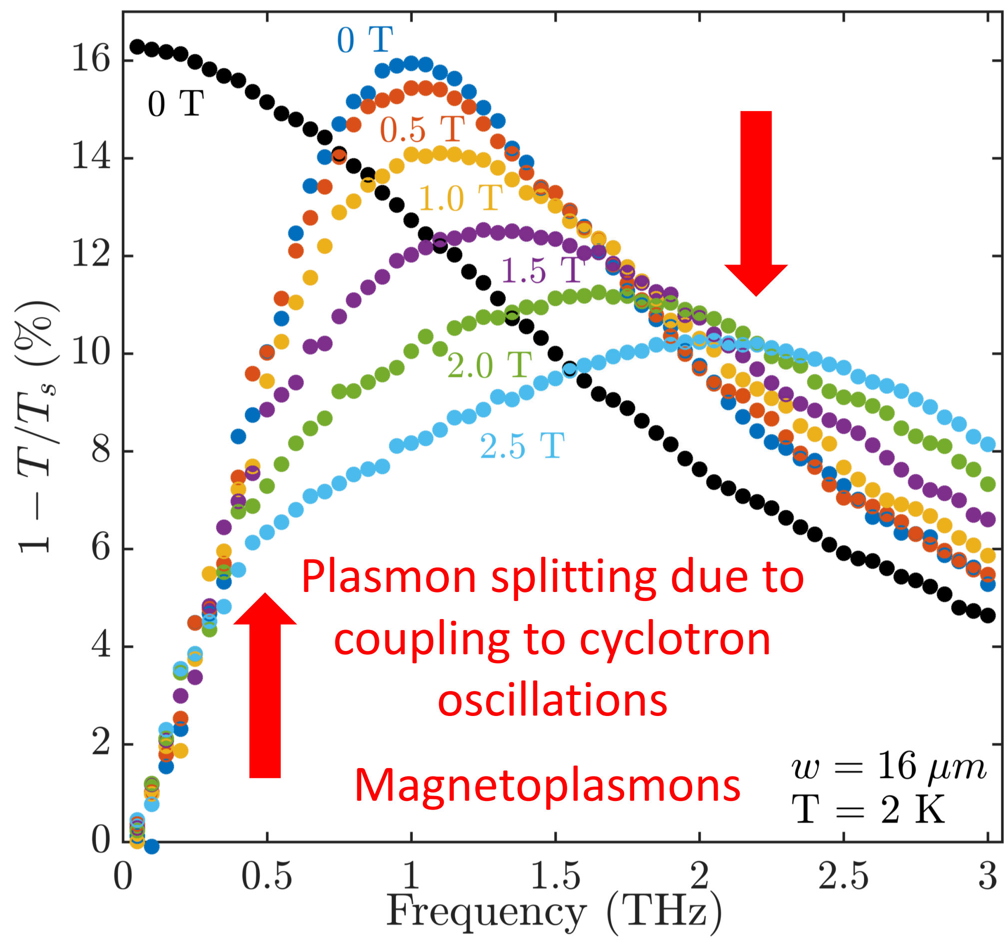




- THz time-domain spectroscopy in 8 T superconducting magnet
- Temperature tuning to 1.3 K
- Wire grid polarizer (WGP) to characterize the THz polarization rotation

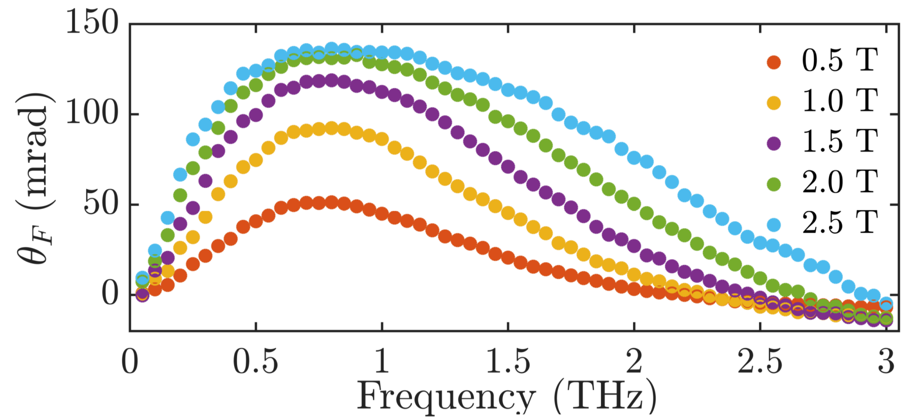
THz transmission spectrum

- Uniform monolayer-like response for THz electric field polarized parallel to long-axis of the ribbons
- Resonance peak shifts to nonzero frequency for E_{THz} perpendicular to the ribbons
- Resonance shift with ribbon width scales as $L^{-1/2}$
- Nonzero magnetic fields broaden the spectrum and yield a pronounced shoulder at high fields



THz Faraday rotation spectrum

- Faraday rotation magnitude is proportional to the magnetic field
- Quadratic scaling of the FWHM with B-field with negligible change in peak position
- Blue shift in the Faraday rotation peak position for smaller ribbon widths
- Roughly constant maximal rotation magnitude and FWHM for different widths



Effective medium model

Optical response of a metasurface can be described by an effective conductivity tensor

$$\overleftrightarrow{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix}$$

- Tensor elements depend on material properties and the interaction of geometric features with the incident field
- For monolayer graphene

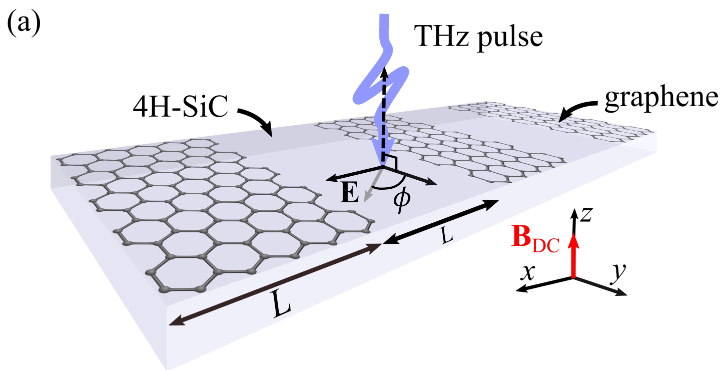
$$\boxed{\sigma_{xx} = \sigma_{yy} = \sigma_0 \frac{1 - i\omega\tau}{(1 - i\omega\tau)^2 + \omega_c^2\tau^2}} \qquad \boxed{\sigma_{xy} = \sigma_0 \frac{\omega_c\tau}{(1 - i\omega\tau)^2 + \omega_c^2\tau^2}}$$

- Optical response can be tuned through the cyclotron frequency (ω_c) dependence of σ_{xx} and σ_{xy}
- Graphene enables dynamic metasurfaces through the application of DC B-fields

Y. S. Cao, et al., IEEE Trans. Antennas Propag. 65, 948 (2017)

Impact of metasurface geometry

- Patterned graphene adds a purely geometric degree of freedom to the metasurface response



- Micro-ribbon pattern is only periodic along x
- THz E-field polarized along the x-axis ($\phi = 90°$) couples adjacent ribbons

Coupling can be modeled by an effective conductivity

$$\boxed{\sigma_C = i\frac{2\omega\epsilon_0\left(\epsilon_r + 1\right)\Lambda}{2\pi}\ln\left[\csc\left(\frac{\pi L}{2\Lambda}\right)\right]}$$

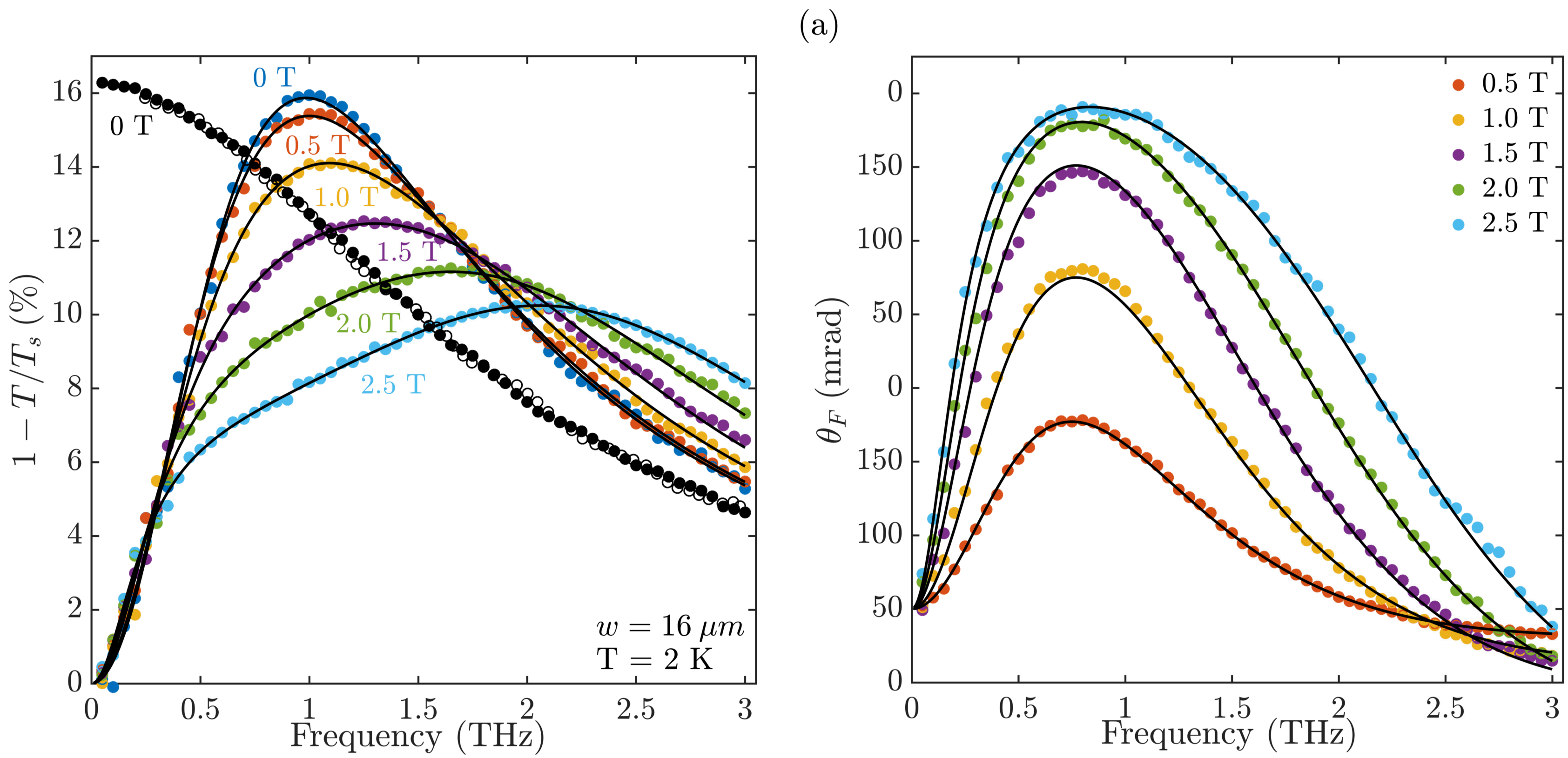
- Effective coupling essentially mixing diagonal and off-diagonal elements:

$$\sigma_{xx}^{'} = \frac{L\sigma_{xx}\sigma_C}{\Lambda\sigma_C + L\sigma_{xx}} \qquad \sigma_{xy}^{'} = -\sigma_{yx}^{'} = \sigma_{xx}^{'}\frac{L}{\Lambda}\frac{\sigma_{xy}}{\sigma_{xx}} \qquad \sigma_{yy}^{'} = \frac{L}{\Lambda}\sigma_{xx} + \frac{L}{\Lambda}\frac{\sigma_{xy}^2}{\sigma_{xx}\sigma_C} - \frac{L}{\Lambda}\frac{\sigma_{xy}^{'2}}{\sigma_{xx}^{'}}$$

- Arbitrary THz polarizations yield weighted sums of σ' terms → THz polarization-dependent response

O. Luukkonen, et al., IEEE Trans. Antennas Propag. 56, 1624 (2008)
J. S. Gomez-Diaz and A. Alù, ACS Photonics 3, 2211 (2016)

Computed THz response



- Solid lines are fits using the effective medium model
- Free floating fit parameters (chemical potential and carrier lifetime) match experimental values for our samples

Graphene micro-ribbon metasurface

- Effective medium model fits both transmission and Faraday rotation data
- Ribbon width and applied external magnetic fields enable:
  1. Control of the THz transmission spectrum through magnetoplasmonic absorption
  2. Independently tuning the range and bandwidth of the Faraday rotation spectrum
- Integration with complementary metasurfaces may allow for enhancement of THz attenuation and polarization rotation magnitudes

Graphene-based metasurfaces offer potential as a flexible, reconfigurable alternative to conventional metallic and dielectric metasurfaces

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